

Quantum Gravity (*and much more...*)

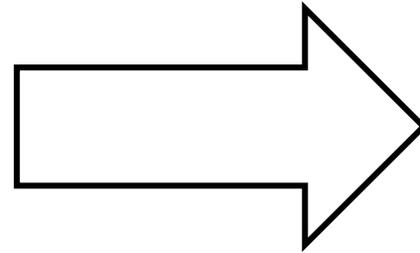
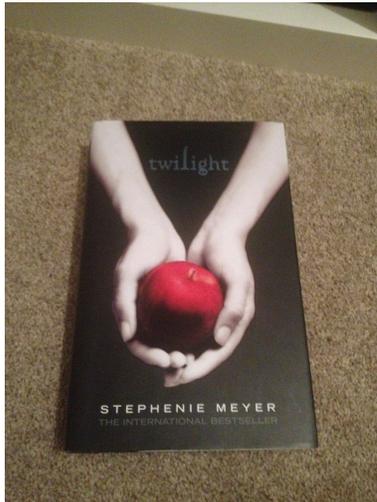
~~High Energy Physics~~ in the Age
of Entanglement

Geoff Penington, UC Berkeley/IAS

New framework/language that enables us to tackle **old problems** - from information in black holes to strongly coupled quantum field theories

Information loss?

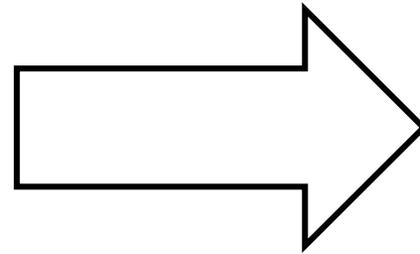
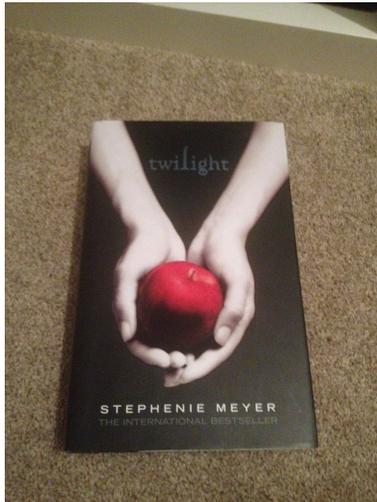
Suppose I have a **book**, and I really want to destroy the information inside. What do I do?



Normally good enough! But maybe not if the NSA (or someone) cares enough...

Information loss?

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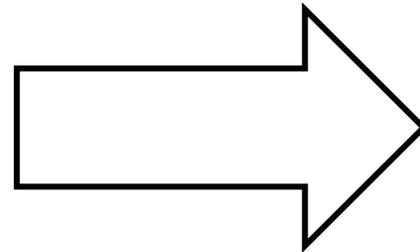
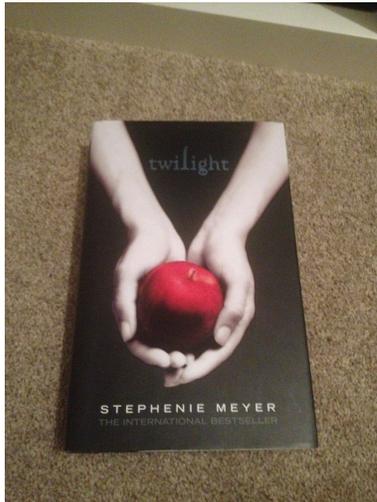


Definitely good enough! But in **principle**, the information in the book is still stored in the positions/momenta of air molecules, photons etc...

 Schrödinger's equation is **unitary**

Information loss?

Suppose I have a **book**, and I really want to destroy the information inside. What do I do?



Hawking (1975): the information genuinely vanishes from the universe (if you wait long enough) => quantum gravity is **not unitary**



2019: first **direct gravitational calculations** showing that he was wrong

Hawking's argument...

Quantum Entanglement

Quantum mechanics is **weird**

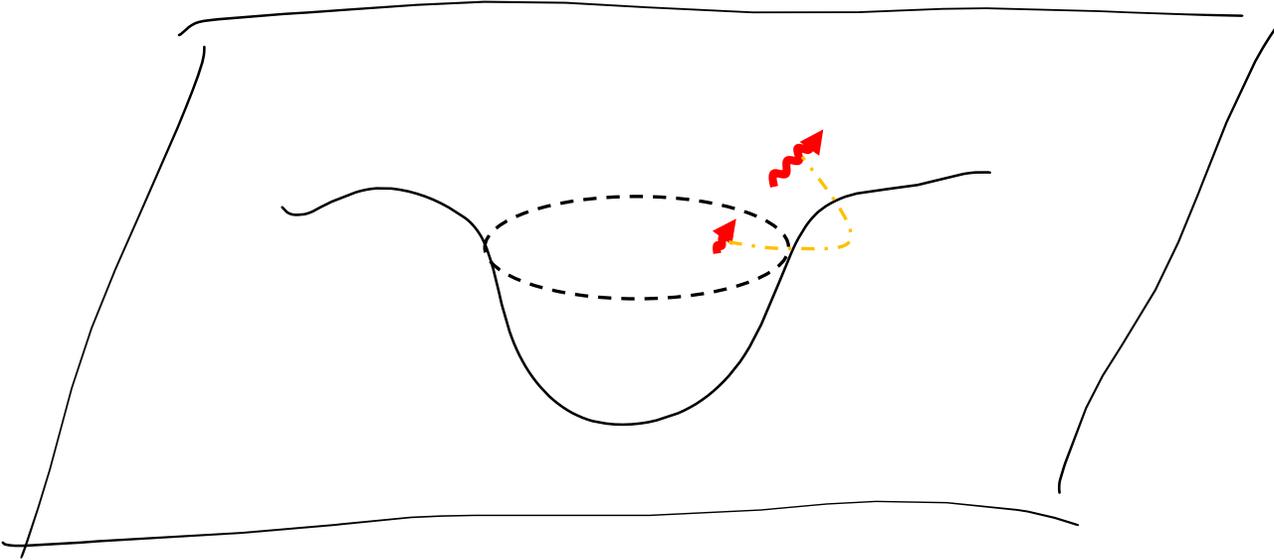
One way its weird: there exist states where the state of the **entire system** is precisely defined, but the states of the **constituent subsystems** are **uncertain/noisy** (described by a **density matrix** ρ)

These are called **entangled states**

$$|\psi\rangle = \frac{1}{\sqrt{2}} [|0\rangle|0\rangle + |1\rangle|1\rangle]$$

Evaporating black holes

Quantum field theory: fields slightly inside/outside the BH horizon are entangled



Evaporating black holes

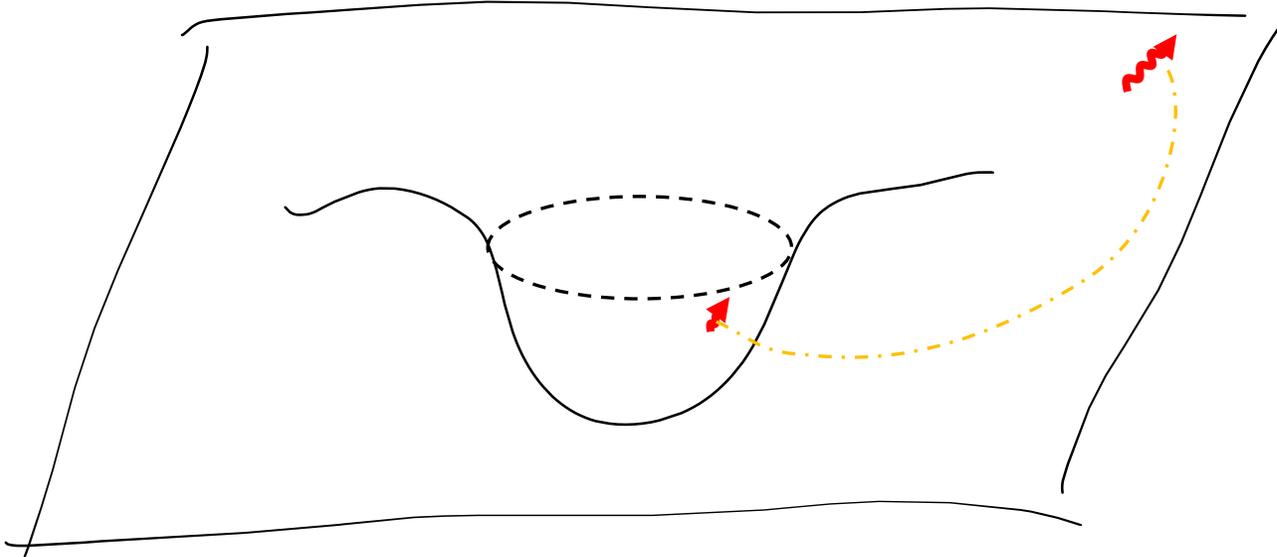
Noisiness of radiation \neq paradox since radiation is entangled with the interior

Quantum field theory: fields slightly inside/outside the BH horizon are entangled

BH dynamics: modes outside horizon escape as thermal **Hawking radiation** that is entangled with the interior modes

$$T = \frac{\hbar c^3}{8\pi G_N k_B M}$$

Quantum \swarrow \searrow Relativity
Circles \nearrow Gravity \nwarrow Thermodynamics



Much **colder** than CMB: no astrophysical black holes are actually losing mass!

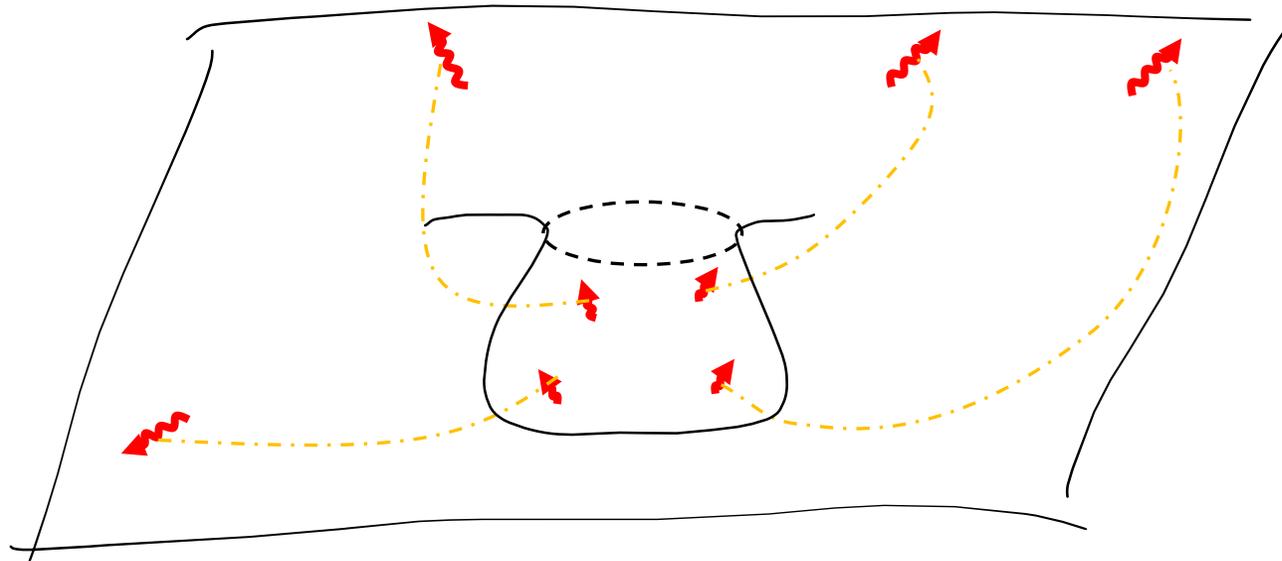
The black hole information problem

As the black holes evaporates, **more and more modes** escape and the black hole gets smaller and smaller.

Eventually the black hole completely evaporates, and we're just left with the **noisy Hawking radiation** = Info loss?

Actually, even when the black hole has $\sim 1/2$ evaporated, the radiation is **too noisy** for the global state to be noiseless

 **Bekenstein-Hawking entropy** formula means the black hole has insufficient degrees of freedom to purify thermal radiation



A loophole?

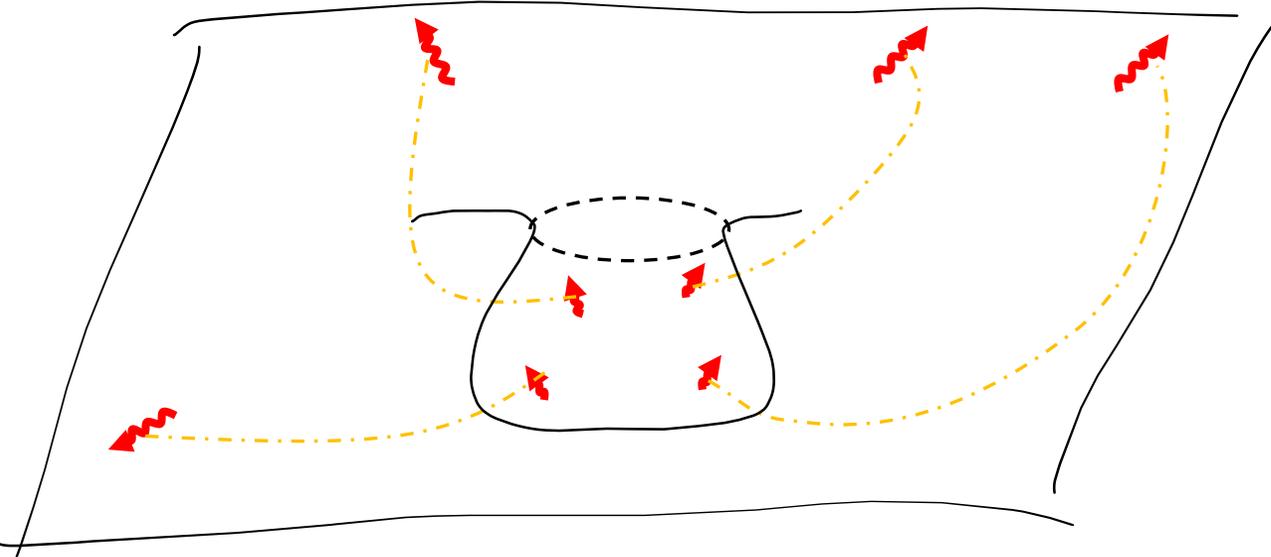
Total amount of Hawking radiation is **very large** ($\sim 10^{70}$ qubits)

Density matrix ρ describing it is **very very large** ($\sim 2^{10^{70}} \times 2^{10^{70}}$)

Hawking's calculation is really computing the **individual elements** of ρ (up to **exponentially small errors**)

Problem: those exponentially small errors can turn a very noisy state into a noiseless one

Solution: directly compute the "noisiness" of the state



Recent Progress...

[**GP**; Almheiri, Engelhardt, Marolf, Maxfield; May 2019]

[**GP**, Shenker, Stanford, Yang; Almheiri, Hartman, Maldacena,
Shaghoulian, Tajdini; November 2019]

The swap test

Standard quantum information protocol to determine whether a state is noisy:

Classical version: distinguish a noisy distribution from an unknown fixed distribution

Impossible with one sample

Take **two samples** and **see if they are the same**

$p(i_1 = i_2) = \sum_i p_i^2$ (= 1 if fixed; $\ll 1$ if very noisy)

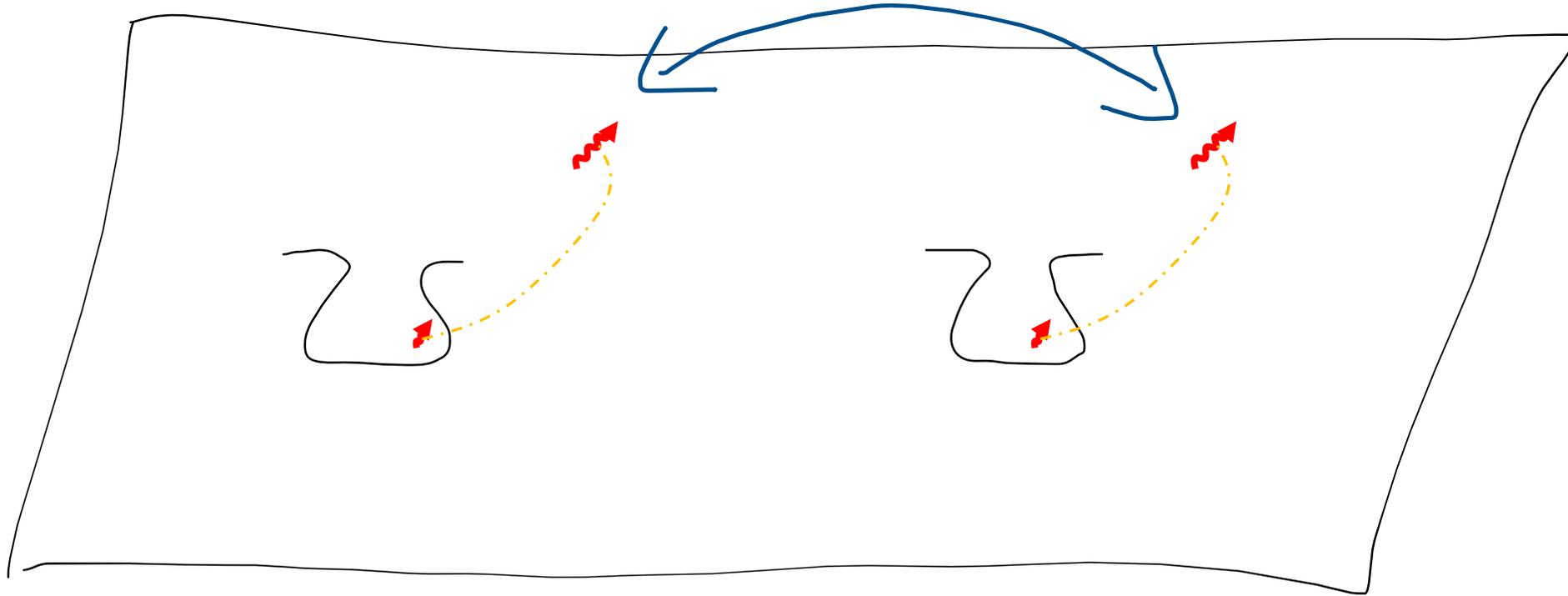
Quantum version: distinguish a noisy state ρ from an unknown pure state $|\psi\rangle$

Impossible with one copy of the state

Take two copies and **measure the "SWAP" operator**

$\langle SWAP \rangle = \text{tr}(\rho^2)$ (= 1 if fixed; $\ll 1$ if very noisy)

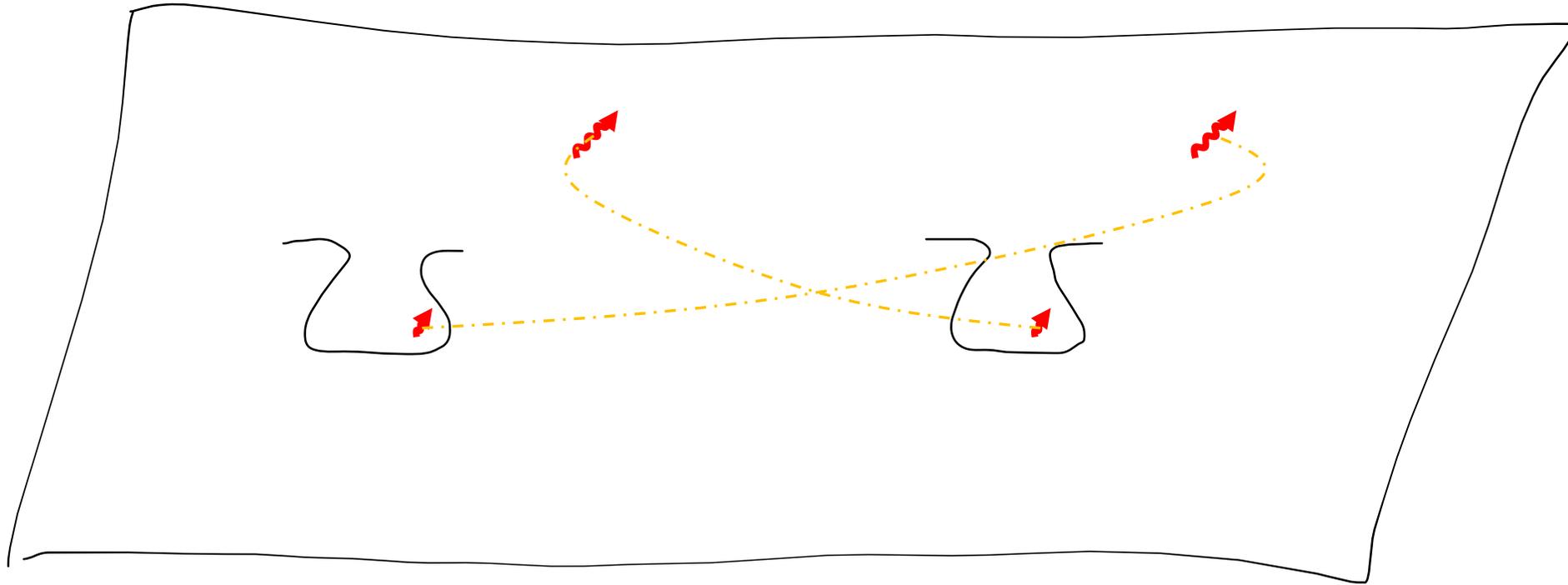
Swap testing black holes



Suppose we swap all the Hawking radiation of two black holes...

Swap testing black holes

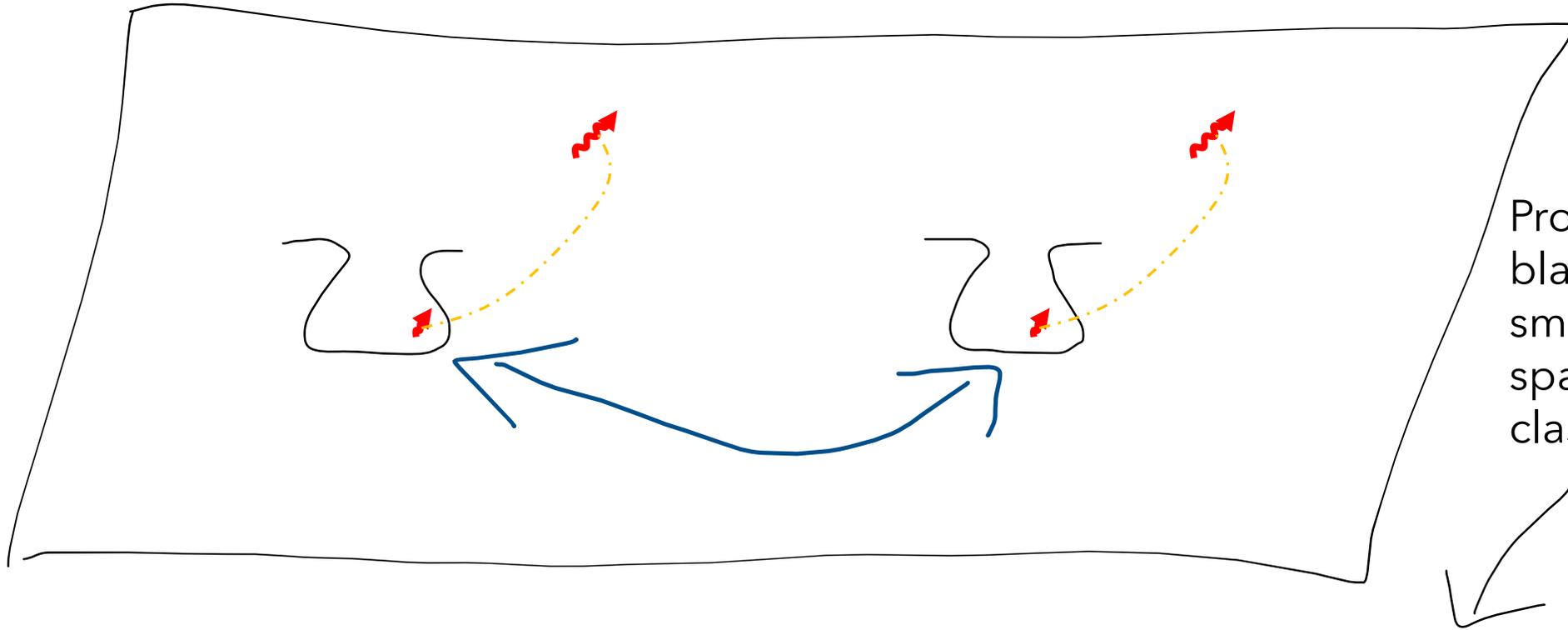
Feynman path integral: integrate over all dynamical variables (including **topology of spacetime**)



If the spacetime geometry was fixed, this would change the state a lot, and so we would have $\langle SWAP \rangle \ll 1$

Wormholes to the rescue

Gives dominant contribution to $\langle SWAP \rangle$ exactly when there would otherwise be an information problem



Probability grows as black hole becomes small and the spacetime is less classical

Exponentially small probability of a **spacetime wormhole** that dynamically swaps the two black hole interiors

Recovering that book

The calculation I just showed you is the simplest way to see that the radiation stops getting noisier

But we can get a **lot more precise**

We can calculate the full **Page curve** for the entanglement entropy of the radiation – the most famous requirement for unitary evaporation

We can even use **quantum error correction** to see how long it takes to recover the information in a book thrown into the black hole, exactly matching a famous prediction by **Hayden and Preskill**

Just like in the swap test, the book gets pulled out through a **spacetime wormhole**

Again, the key tool (the “**Petz map**”) is a standard technique from quantum information, applied in a very new context

Where next?

Quantum information is a framework

We've known for 50 years that the way black holes process quantum information is important in quantum gravity, so it's unsurprising that quantum gravity has seen many of the most prominent applications of quantum information to fundamental physics

But the applications are much broader than that: information theory gives a new way to ask about things we've always cared about (quantum field theory, many body physics etc.).

E.g. rather than study one correlation function, study the mutual information underlying all correlation functions; quantum error correction is not about implementing Shor's algorithm - it's about how information is localised in quantum subsystems.

Even in quantum gravity we're only just scratching the surface of what can be done. Every day there are new applications of both traditional QI tools (e.g. von Neumann algebras) and new tools we are inventing ourselves (non-isometric quantum codes).

Many really hard conceptual questions remain, but these are exciting times!